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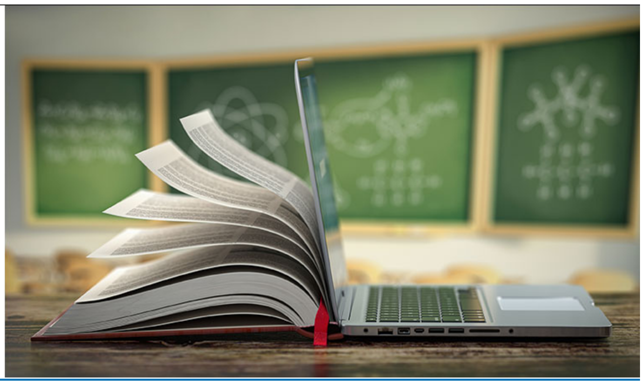

Analysis of the methods for accounting the renewable and non-renewable resources in scheduling

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Abstract. The paper discusses a scheduling problem taking into account the constraints on the renewable and non-renewable resources and availability of the works due dates. For the problem, an overview of the scheduling methods is given. The considered scheduling methods include approximate optimization algorithms and hybrid algorithms based on the genetic algorithm. It is concluded that it is necessary to use heuristic methods to find a solution. A new hybrid scheduling method based on multi-agent simulation is proposed. Application of agent-based simulation allows one to take into account the life cycle of the non-renewable resources and to distribute the renewable resources during scheduling. The genetic algorithm ensures search for the effective schedule with aim at the minimum cost of attracting the additional renewable resources in order to maintain the works deadlines.

1. Introduction

Business processes scheduling is a key control problem of the organizational systems. Considered business processes include processes of the project portfolio performing with application of the subcontract resources.

We consider the project scheduling problem with the goal of determination of such a schedule that ensure fulfillment all the works according to the due dates with application of the shifting of the works start in a given period. The renewable and non-renewable resources are used to fulfill the works. The renewable resources can be reused after their release. The non-renewable resources are fully consumed during works fulfillment, for example, concrete in the construction work.

One of the main problems that a decision-maker encounters in scheduling is contradictions between the works deadlines and the restrictions on the renewable resources [1-9]. A way of overcoming the problem is application of the subcontract renewable resources in absence of the own ones. Thus, the goal of scheduling in addition to meeting the due dates is to reduce the cost of attracting subcontract resources.

Enterprises of various fields of activity are faced with similar problem, for example, manufacturing and project organizations that flexibly respond to the changing demand by attracting the subcontract resources if necessary. The decision time during scheduling should not exceed a critical value to ensure timely response to the changes in demand. Ineffective scheduling can lead to financial losses.

Thus, a topical problem is development of the scheduling method considered optimization of the subcontract resources cost, presence of the time constraints and restrictions on the resources of the renewable and non-renewable type.

2. Scheduling problem formulation

We consider the project portfolio that has the following characteristics:

- P is number of the projects, $p = 1, \dots, P$;
- N_p is number of the operations of the project p with index $i = 1,2, \dots, N_p$;
- R is number of the renewable resources of the allocated competency, $r = 1, \dots, R$;
- R^* is number of the non-renewable resources of the allocated type, $r^* = 1, \dots, R^*$;
- $Pr_p = \{Op_i\}_{i=1,\dots N_p}$ is set of the operations of the project p;
- t_0 and T are start and end times of scheduling;
- Q_r is available quantity for each renewable resource r;
- Q_{t_0,r^*} is initial quantity for each non-renewable resource r^*.

We have identified for each operation i of the project p the following characteristics:

- $d_{p,i} \geq 0$ is operation duration;
- $q_{p,i,r} \geq 0$ is required amount of the renewable resources of the allocated competency;
- $q^-_{p,i,r^*} \leq 0$ and $q^+_{p,i,r^*} \geq 0$ is amount of the non-renewable resources of the allocated type consumed at the start of the operation and produced at the end of the operation respectively;
- $s_{p,i,r} \geq 0$ is the cost of one day of performing the operation with a single amount of the renewable resource of the allocated competency;
- $\tau^0_{p,i} \geq 0$ and $\tau^1_{p,i} \geq 0$ are the early and late operation start times that set restrictions on the operation start time $x_{p,i}$.

We assume that the set of operations for each project p is ordered in increasing the cost $s_{p,i,r}$.

It is required to find the schedule of the projects portfolio determined by the operations start times $x_{p,i},\ p = 1,2, \dots, P,\ i = 1,2, \dots, N_p,\ x_{p,i} \in \mathbb{Z}^+, \mathbb{Z}^+ = \{0,1,2, \dots\}$.

We denote the set of indices of the operations performed at the time $t \geq t_0$ and using the resource r as follows:

$$I(t,r) = \{ i = 1,..,m \mid x_{p,i} \leq t < x_{p,i} + d_{p,i} \ \&\ q_{p,i,r} \neq 0 \ \&\ Op_i \in Pr_p \ \&\ p \in [1,P] \}. \quad (1)$$

At each moment of time t, for each of the renewable resources of competency r the following situations are possible:

- $\sum_{p\in[1,P]} \sum_{i\in I(t,r)} q_{p,i,r} \leq Q_r$ if at the time t all operations with index $i \in I(t,r)$ are performed by the own resource of competency r;
- $\sum_{p\in[1,P]} \sum_{i\in I(t,r)} q_{p,i,r} > Q_r$ in the case of attracting at the time t an additional (subcontract) amount of the resource of competency r to perform operations with index $i \in I(t,r)$.

We denote the set of indices of the operations performed at the time $t \geq t_0$ and using their own resource r within the available amount Q_r:

$$I^{\sim}(t,r) = \{ i = 1,..,m^{\sim} \mid i \in I(t,r) \ \&\ \textstyle\sum_{p\in[1,P]} \sum_i q_{p,i,r} \leq Q_r \}. \quad (2)$$

The set of indices of the operations performed at the time $t \geq t_0$ and using the subcontract resource r is defined as follows:

$$I^*(t,r) = \{ i = 1,..,m^* \mid i \in I(t,r) \ \&\ i \notin I^{\sim}(t,r) \}. \quad (3)$$

The idle time of the own resources of competency r in percentage when executing the project p at the time t is calculated by the formula:

$$Z_{p,t,r} = \begin{cases} \left(1 - \sum_{i\in I^{\sim}(t,r)} q_{p,i,r}/Q_r\right) \cdot 100\%, & i \in I^{\sim}(t,r) \ \&\ Op_i \in Pr_p, \\ 0\%, & i \in I^*(t,r) \ \&\ Op_i \in Pr_p. \end{cases} \quad (4)$$

The percentage workload of the resource r performing project p at the time t is defined as follows: $U_{p,t,r} = 100\% - Z_{p,t,r}$.

The cost of the involved subcontract resource of competency r for implementation of the project p at the time t is calculated by the formula:

$$SC_{p,t,r} = \textstyle\sum_{i\in I^*(t,r)} s_{p,i,r} q_{p,i,r}. \quad (5)$$

The current volume of the non-renewable resource r^* at the time t is defined by the formula:

$$Q_{t,r^*} = Q_{t_0,r^*} + \sum_{t'=t_0}^{t} \sum_{p=1}^{P} \sum_{\substack{i \in I(t',r^*) \\ \wedge (t'=x_{p,i})}} q^{-}_{p,i,r^*} + \sum_{t'=t_0}^{t} \sum_{p=1}^{P} \sum_{\substack{i \in I(t',r^*) \\ \wedge (t'=x_{p,i}+d_{p,i})}} q^{+}_{p,i,r^*} \quad (6)$$

The scheduling problem is formalized as follows:

$$\sum_{p=1}^{P} \sum_{t=t_0}^{T} \sum_{r=1}^{R} SC_{p,t,r} \to min \quad (7)$$

$$\sum_{p=1}^{P} \sum_{\substack{i \in I(t,r^*) \\ \wedge (t=x_{p,i})}} \left| q^{-}_{p,i,r^*} \right| \le Q_{t,r^*}, t = t_0, .., T, r^* = 1, .., R^* \quad (8)$$

$$\tau^0_{p,i} \le x_{p,i} \le \tau^1_{p,i}, \;\; p = 1, .., P, i = 1, .., N_p, x_{i,p} \in \mathbb{Z}^+ \quad (9)$$

The objective function (7) minimizes the total cost of the attracted subcontract resources in the case of exceeding availability of the own renewable resources. The constraint (8) ensures availability of the required amount of the non-renewable resources at the time of the start of execution of each of the operations requiring the use of the non-renewable resources. The constraint (9) imposes a time frame on the start dates of the operations.

3. The scheduling methods with the renewable and non-renewable resources

The scheduling problem belongs to the class of problems studied by the theory of scheduling and network planning [1-3]. In the general case, the considered optimization problem with the resource constraints and works deadlines is algorithmically complex. To solve such problems, either approximate algorithms or heuristics that narrow the search space are used.

3.1. Critical path method

A critical path method (CPM) is intended for determining the critical path and reserve time for planning with deterministic operations duration [4]. A PERT method generalizes the critical path method for the case of probabilistic operations duration. A GERT method extends the PERT method by taking into account the probabilities of implementation of the individual projects [5,6]. An important aspect of the network methods is presence of the precedence-succession relations because the critical path is calculated by analyzing the operations relations and durations.

3.2. Gimadi method

The scheduling problem which aimed at the projects portfolio duration minimization considering the precedence-succession constraints, due dates, and restrictions on the renewable and non-renewable resources has been decided by Gimadi [2]. For the considered problems, Gimadi proposed an approximate algorithm, which at the preliminary stage converts the initial data to the network model and indicates contradictions between the resource constraints and deadlines (which should not be in the algorithm), and also solves the problem of finding the critical path without regard to the resource constraints. At the first stage, the algorithm [2] calculates the estimated feasible schedule under the assumption that all resources are non-renewable. At the second stage, the algorithm [2] searches for the feasible schedule considering the renewable resources constraints by packing works in order to satisfy all resource constraints and minimize the execution time. Advantages of the algorithm are consideration of the deadlines, consideration of the limited renewable and non-renewable resources, and calculation the estimate of the deviation of the approximate solution from the exact one. Disadvantage of the algorithm is exclusion from consideration of such an arrangement of works, in which contradictions arise between the resource constraints and works deadlines (for example, for works on the critical path there can be excess of availability of the own renewable resources). In this case, enterprises can use the subcontract renewable resources, the cost of which need to be optimized. This circumstance remains outside the scope of the Gimadi algorithm work.

Gimadi proposed an approximate algorithm for solving the scheduling problem defined according to [1] as $PS/prec/C_{max}$, with limited non-renewable resources consideration and works deadlines, works interruptions are not allowed. For the proposed algorithm, an assess of the complexity and a lower estimate of the optimal schedule length are given. During the algorithm work, two cases are excluded from consideration as situations in which the problem has no solution: 1) the case when the earliest schedule, the length of which is equal to the length of the critical path, does not satisfy the constraints on the works due dates, 2) the case when for at least one type of the resource the total volume of the non-renewable resources required for works execution exceeds the total volume of the produced resources. However, for the first case, the solution can be found by attracting the subcontract resources to perform works on the critical path. For the second case, decision can be associated with implementation of the flexible supplies of the non-renewable resources depending on the current and required resources volumes. Description of the scenarios for attracting the subcontracting resources and flexible supply of the non-renewable resources based on the knowledge of the decision maker is supported using multi-agent simulation.

3.3. Goncharov method

Goncharov considers the above scheduling problem in which interruptions are not allowed. In the literature [3], a heuristic method based on the modified genetic algorithm for solving the high-dimensional scheduling problem is proposed by Goncharov. Modification of the genetic algorithm is associated with the concept of a 'dense gene' – chromosome section that encodes a sequence of the works that mostly optimal use the renewable resources (with the smallest remainder of the free resources). Also in the paper [3], the scarcity of the renewable resource is determined by solving the simplified scheduling problem with assumption that all resources are non-renewable and determining the remaining of the free resources. The quality of the proposed algorithm [3] has been studied using examples from the electronic library of the test problems. Advantages of the proposed heuristic algorithm [3] are orientation towards solving problems of the large dimension and high quality of the solutions found; disadvantages include lack of consideration of the works deadlines and lack of accounting the restrictions on the non-renewable resources.

Application of the heuristic methods of evolutionary modeling to the scheduling problem is considered in the literature [7,8]. In the scientific publications on the topic of research, the problem of optimizing the cost of the attracted subcontract renewable resources and accounting for the discrete limited non-renewable resources is not given due attention.

Thus, development of a method and computer technology for scheduling taking into account the renewable and non-renewable resources and reducing the cost of the subcontract resources based on a hybrid heuristic method of simulation-evolutionary modeling is of scientific and practical interest.

3.4. Multi-agent genetic optimization method

The use of simulation and multi-agent modeling for solving the scheduling problem allows one to take into account all given constraints of the problem (8)-(9). Agent modeling provides accounting the life cycle of the non-renewable resources and attracting the subcontract renewable resources in the case of exceeding availability of the own ones, which makes it possible to increase the adequacy of the developed process simulation model. Disadvantages of this approach include the need to form a plan of experiments that would contain an effective solution in terms of reducing the cost of the subcontract resources, which in the case of a full-factor experiment is resource-intensive in terms of computer time. Application of a fractional-factor experiment requires knowledge of a priori information about the significance and insignificance of the main factors interactions and is also resource-intensive in terms of the computer time. For example, for 35 analyzed operations, the estimate of the number of experiments for finding a schedule is 2^{35} and 2^{10} experiments respectively for full-factor and fractional-factor planning. Application of the hybrid heuristic-simulation algorithms that reduce the search space for solving the business processes scheduling problem is relevant. Application of the methods of evolutionary modeling, in particular the genetic algorithms, makes it possible to overcome identified disadvantages of the previous methods.

In order to take into account the identified factors, a hybrid method of simulation-evolutionary modeling has been developed, which has been implemented in the new method of multi-agent genetic optimization (MGO). The proposed MGO method allows one to search for a solution to the scheduling problem. The multi-agent model is intended to assess the fitness function of the solutions during the genetic algorithm work. The controllable parameters (start dates of the project works) and initial parameters are fed to the input of the multi-agent model. The parameters formed in the decision-making process are the outputs of the model: the cost of attracting subcontract resources and downtime of the own resources of each competence. In the model, the agents are used to implement the algorithm for allocating the renewable and non-renewable resources according to the formula (8).

3.5. Comparative analysis of the scheduling methods

Comparative analysis of the scheduling problem solved by the considered algorithms is given in table 1. For all algorithms, the authors give an estimate of the deviation of the approximate problem solution from the exact one and the complexity of solution finding. As follows from the table, none of the methods except for the MGO method has full functionality for solving the problem under consideration. None of the methods supports optimization of the cost of the attracting subcontract resources to ensure the required quality of the solution according to the formula (7). Only the Gimadi method and MGO method provide accounting the non-renewable resources (supplies and consumption) to fulfill the constraints (8); only the MGO method takes into account the lifetime of the non-renewable resources. In general, all analyzed scheduling methods are aimed at solving the problem of balancing the renewable resources in order to minimize the execution time of the project portfolio.

Disadvantages of the MGO method include lack of the mechanisms for minimizing the length of the schedule and lack of accounting the function of continuous consumption (production) of the non-renewable resources. These shortcomings are associated with the specifics of the analyzed subject area: discreteness of the considered business processes and presence of the time frames for implementation of the projects and therefore no dense packing of the projects' works is required.

Table 1. Comparative analysis of the scheduling problem decision methods.

Assessment criterion	**CPM method**	**Gimadi method**	**Goncharov method**	**MGO method**
Accounting and balancing the renewable resources	YES	YES	YES	YES
Accounting the non-renewable resources (consumption and production)	NO	YES	NO	YES
Accounting the lifetime of the non-renewable resources	NO	NO	NO	YES
Accounting the subcontract renewable resources	NO	NO	NO	YES
Schedule makespan minimization	YES	YES	YES	NO
Subcontract resources cost minimization	NO	NO	NO	YES
Estimation of the distance between the approximate solution and the optimal one	Comparison with the critical path length	Comparison with the critical path length	Comparison with the simplified schedule length	Comparison with zero subcontract cost Ss/c=0
Estimation of the number of iterations, where: N – amount of the scheduled works, N_{pop} – number of the genetic algorithm populations, N_{ch} – number of the populations' chromosomes, k – polynomial degree	N^2	$N\log_2 N$	N^k	$N_{pop}N_{ch}$

The obtained theoretical results (the method of multi-agent genetic optimization) made it possible to implement software belonging to the class of intelligent decision-making systems [9]. This software has been applied to solve the problems of scheduling of the organizational processes aimed at eliminating incidents and problems of scheduling of the organizational processes for telecommunication support of the metallurgical rolling shops [9].

4. Conclusion

In the paper, the scheduling problem has been posed taking into account optimization of the costs for attracting the subcontract renewable resources, limited non-renewable resources and works deadlines. A new method of multi-agent genetic optimization has been developed for the scheduling problem. The developed method of multi-agent genetic optimization has been compared with the existing ones: the critical path method, the scheduling method based on the Gimadi optimization algorithm, and Goncharov method, which involves planning using integration of the genetic algorithm and scheduling theory. Comparison showed the following advantages of the new method for solving the given scheduling problem: optimizing the costs of attracting the renewable subcontract resources and accounting the non-renewable resources when planning (production and consumption, resource life). The obtained theoretical results allowed one to implement software that uses the methods of multi-agent and evolutionary simulation to solve the problem of the business processes scheduling.

One of the ways to improve the developed hybrid method is to solve the multicriteria problem of finding a schedule that is optimal in terms of the schedule length and cost of the outsourced renewable resources.

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